Climate and Geo-Sciences

A Challenge for Science and Society in the 21st Century

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CLIMATE RESPONSE TO GREENHOUSE WARMING: THE ROLE OF THE OCEAN

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1. Introduction

The scientific community is now confronted with unambiguous evidence that the abundance of radiatively important gases in the atmosphere is changing. The scientific tools exist to calculate the effect of these gases on the Earth's radiation balance. Is it then possible to draw firm conclusions with respect to projected climate change over the next half century? The answer is no, even if all processes internal to the atmosphere were completely understood. Climate change does not depend on the radiation balance of the atmosphere alone, but on the entire climate system, which includes the oceans, the biosphere polar ice masses and sea ice. Climate projections into the next century cannot be made with confidence until the role of the extra-atmospheric components of climate are better understood.

The purpose of this paper is to review the status of research on the ocean's role in climate change. For purposes of conceptualizing the role of the ocean in a period of rapid change in the Earth's environment we can imagine two extreme situations. In one case the World Ocean would simply be a shallow swamp, without heat capacity. In that situation the climate would respond rapidly to a change in the heat balance of the atmosphere, the only lags due to slow changes in the biosphere and the polar ice masses. The time scale of response of the atmosphere alone would only be of the order of few months (Hoffert et al., 1980). The other extreme situation would be one in which the ocean was well mixed on short time scales from top to bottom. Since the heat capacity of the ocean is more than three orders of magnitude greater than the atmosphere, the response time of the combined atmosphere ocean system would be a thousand times a few months, or several centuries. If surface waters were perpetually well mixed with deep waters, greenhouse warming of climate would not be appreciable for many decades.

Marine geochemistry provides some evidence to narrow down the range of possibilities between these two extremes. In the late 1950's and early 1960's bomb tests created an invasion of tritium and bomb-produced ^{14}C into the upper ocean. Tritium largely entered into

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the Northern Hemisphere Oceans, but the invasion of bomb-produced ^{14}C was more uniform over the globe. The GEOSECS and TTO programs provide a partial description of how these tracers penetrate into the ocean. Recently, the invention of a device to measure chlorofluorocarbons (CFC's) in the oceans has opened up another source of information on vertical pathways. If it is assumed that a change in climate is sufficiently small so that the ocean circulation will not be significantly changed from its present state, then one can expect that warm and cold anomalies at the ocean surface will be carried downward in the same way as a passive tracer. In the following section we will show how this idea has been applied to project climate change.

2. Geochemical Modelling

A simple and elegant model for analyzing transient tracers was developed by Oeschger et al. (1975). The World Ocean is represented in a one-dimensional model, consisting of a deep diffusive layer capped by a well mixed slab at the surface. This basic model is frequently referred to as the "box-diffusion" model. It is a very useful conceptual tool for describing observations as well as the solutions of more complex models, (e.g. Schlesinger et al., 1985). In the box layer, $0 > z > -h$,

$$h \, \partial_t \alpha = F^s - F^h \tag{1}$$

where F^s is the flux of tracer with mixing ratio α through the surface and F^h is the flux of tracer through the base of the mixed layer. In the diffusive slab below, $-h > z > -H$,

$$\partial_t \alpha = K \, \partial_{zz} \alpha \tag{2}$$

where K is the vertical diffusivity and the boundary conditions are,

$$K \, \partial_z \alpha = F^h \qquad z = -h$$

and

$$\partial_z \alpha = 0 \qquad z = -H .$$

Observations taken during GEOSECS (Sarmiento, 1983) show that although tritium rapidly invaded the upper thermocline in the decade after the bomb tests, only a relatively small fraction (less than 10%) has penetrated into the North Atlantic deep water. The "box-diffusion" model is able to simulate the difference in time scales between the surface and deep water. In the model, tracer is rapidly taken up in the mixed layer and diffused rapidly into the upper part of the water column. As vertical gradients diminish with increasing depth, the downward penetration greatly slows down. However, Bacastow and Bjorkstrom (1981) point out that there are limitations to the quantitative application of the box-diffusion model to real data. The box diffusion model has essentially two adjustable parameters, h and K. These authors show that a careful calibration of these two parameters to bomb-produced ^{14}C data, does not give a good fit to the distribution of natural ^{14}C in the lower thermocline. They attribute this to the fact that the pathways to the deep water originate at very high latitudes, while the downward pathways to the main thermocline originate at the surface in middle latitudes. One could not expect that such very different processes could be precisely fitted by the same two parameter model with identical coefficients.

This has led to the development of more elaborate geochemical models in two and three dimensions. Of particular interest is the 12 box World Ocean model developed by Bolin, Bjorkstrom, Holmen and Moore (1983) which has recently been extended to an 84 box model of the Atlantic. The objective of this group has been to use geochemical data to construct the currents and mixing of the ocean by inverse methods. The calculated circulation is then used in a "forecast" model to predict the invasion of transient tracers such as tritium and bomb-produced ^{14}C. The only dynamical constraint introduced is the geostrophic vertical shear along east-west sections compatible with observed temperature and salinity distributions. The model provides a very reasonable picture of the total overturning circulation in the Atlantic and a good simulation of the transient tracers, although the horizontal resolution is not good enough for very detailed comparison with observations.

A pioneering simulation of transient tracers with a three-dimensional model was carried out by Sarmiento (1983). The ocean circulation used to transport the tracers was generated by the diagnostic model of Sarmiento and Bryan (1982). In this diagnostic calculation a 12 level numerical model of the North Atlantic is forced into a steady solution by a numerical integration with respect to time in which the predicted values of temperature and salinity are partially replaced by the observed values at each time step. The partial replacement parameter governs whether the emphasis is on a close fit to the data or to the model. Sarmiento's (1983) calculations demonstrate that winter-time convection is a much more important vertical pathway for tritium in the North Atlantic than is downward Ekman pumping.

Recently Maier-Reimer and Hasselmann (1988) have studied both the distribution of Carbon-14 and Tritium in a model of the World Ocean. In this case the ocean circulation model was time-stepped to equilibrium with only temperature and salinity specified at the surface. The tritium simulation for a north-south section in the Atlantic is compared to GEOSECS data in Fig. 1. Although the simulated penetration is not quite deep enough in the high latitudes of the North Atlantic and perhaps a little too deep near the equator, the observed pattern is captured by the model in remarkable detail. Fig. 1 illustrates how the transient tracer data are a powerful tool for validating ocean models. Similar validation experiments are being carried out which test ocean general circulation models with bomb-produced Carbon-14 and CFC (freon) data. It is a great advantage

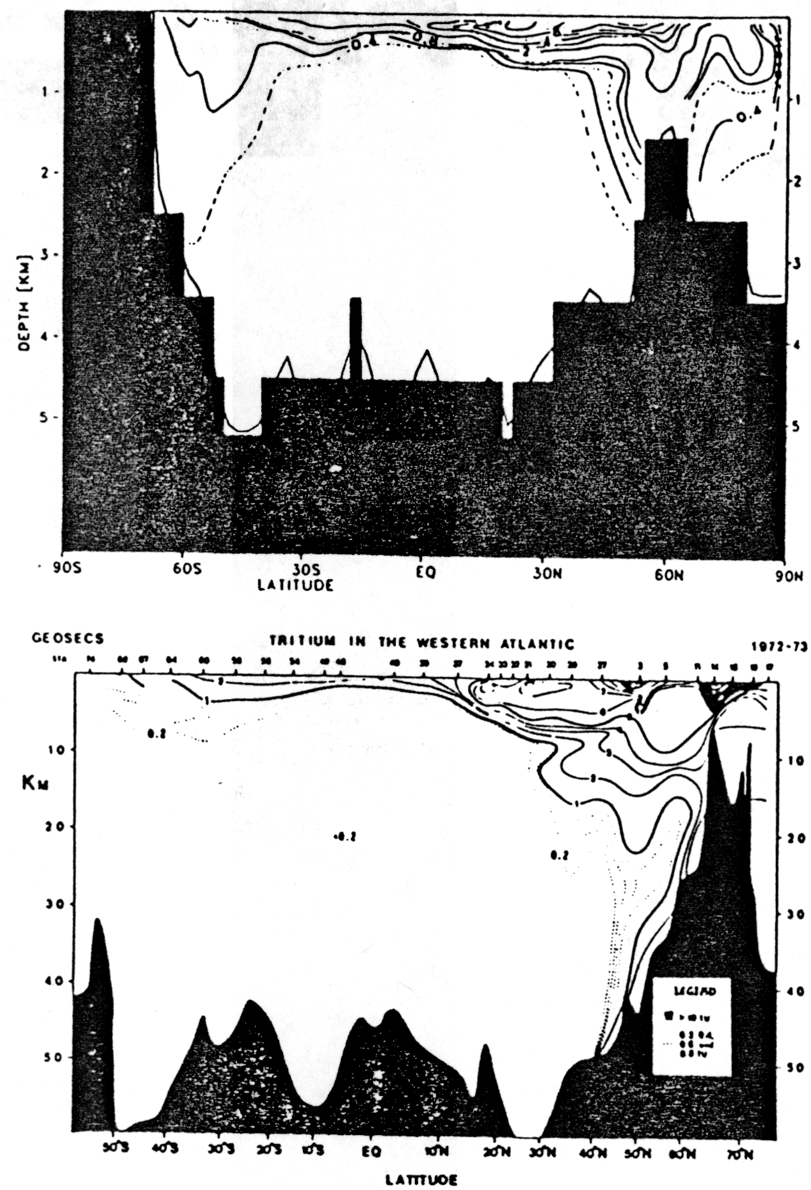


Figure 1. (a) A simulation of the penetration of Tritium into the Atlantic Ocean in a model of the World Ocean (Maier-Reimer and Hasselmann, 1988), (b) Tritium observations along a GEOSECS section made in 1972 in the Western Atlantic. tritium units.

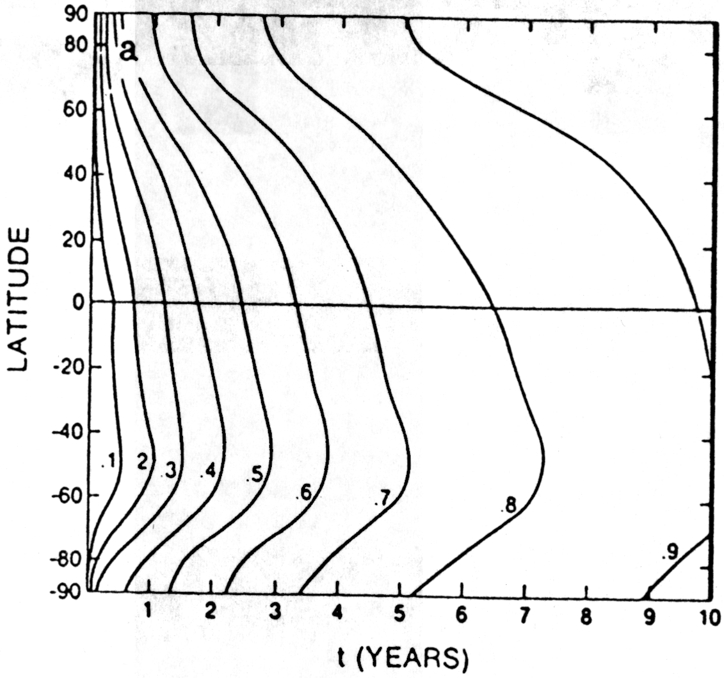
to use several tracers, which have somewhat different source distributions at the ocean surface. A variety of different tracers will test the model's ability to simulate different pathways from the surface to the deep ocean, since pathways at all latitudes may be important as the ocean responds to greenhouse warming.

3. Energy Balance Models of the Ocean

The counterpart of the one-dimensional geochemical model of the ocean is the energy balance climate model (Hoffert and Flannery, 1985). The unmodified box-diffusion model is not satisfactory to represent the ocean's temperature structure, since diffusion would mix out the thermocline in an equilibrium state. A modification of the model adds a uniform upwelling, adding a third parameter. Hoffert et al. (1980), Cess and Goldenberg (1981) and Harvey and Schneider (1985) have used this type of model coupled to an energy balance model of the atmosphere to predict the effect of the ocean in the case of a carbon dioxide warming event. With a calibration based on transient tracers, these studies indicate that, because the warming of the ocean would be confined to the upper thermocline, climate warming would be delayed only a few decades by the ocean. This is quite different from a delay of centuries which would be expected if the entire ocean were well mixed.

Schneider and Thompson (1981) extended energy balance model studies of greenhouse warming to resolve differences of ocean mixing and land/ocean surface area at different latitudes. With a minimum of parameters their model takes into account the proportion of ocean at each latitude and the increase in depth of mixing by winter convection as one goes to higher latitudes. On the basis of this coupled ocean-atmosphere energy balance model Thompson and Schneider (1982) concluded that warming would take place much more rapidly in the Northern Hemisphere than the Southern Hemisphere. In a further refinement North et al. (1984) developed an energy balance model with a two-dimensional coverage of the entire globe. Applying this model to the actual ocean-land distribution, the authors confirm that temperature rise takes place much more slowly in the Southern Hemisphere. The results shown in Fig. 2 are for a "switch on" experiment in which the atmospheric carbon dioxide is suddenly doubled. The zonally averaged temperature normalized by the total expected change is shown as a function of latitude and time. Note that the parameterization of the ocean in this model implies, on the whole, a rather small impact of the ocean on climate change. In the Northern Hemisphere nearly 80% of the response has taken place within 5 years. In the Southern Hemisphere the delay is longer, as predicted by Schneider and Thompson (1981), but even there 80% of the response has taken place after 7 years.

As Hansen et al. (1984) point out, the speed of the response of a given model depends on how strong the feedback mechanisms are. The stronger the positive feedbacks the slower the approach to final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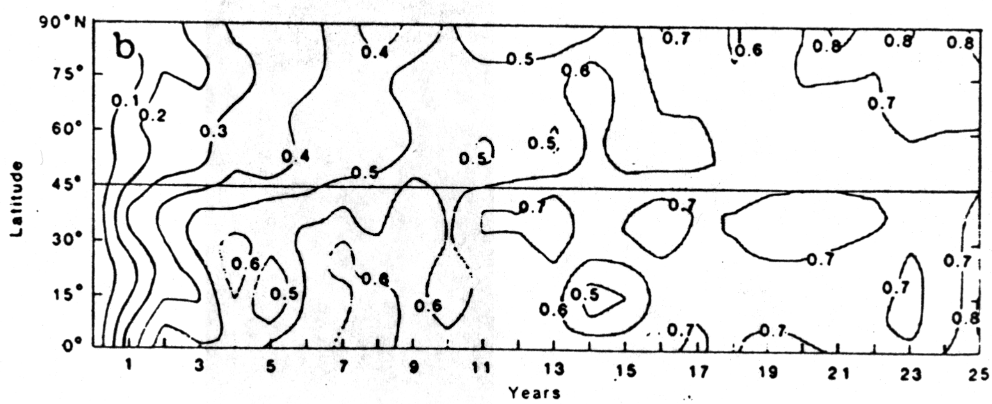
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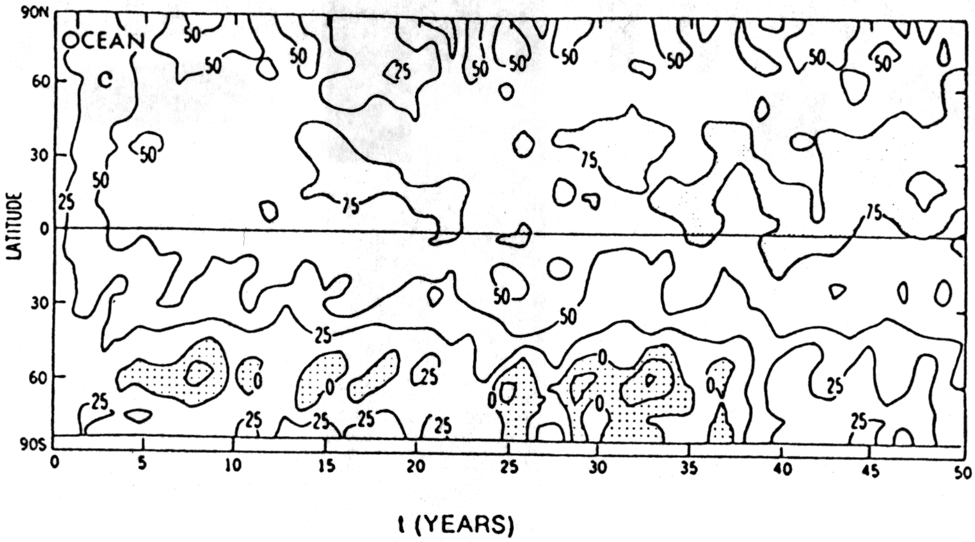

Figure 2. Air temperature response when atmospheric carbon dioxide is suddenly increased to a higher value. The zonally averaged and normalized temperature change is shown as a function of latitude and time after "switch on". Normalization is with respect to the temperature change expected for complete adjustment to the high atmospheric carbon dioxide. (a) Results of North et al. (1984) for two-dimensional, global energy balance model including a passive ocean. Carbon dioxide is doubled. (b) Results of the coupled ocean-atmosphere general circulation model of Bryan et al. (1982). Carbon dioxide in the atmosphere is increased four times. (c) A two hemisphere coupled atmosphere-ocean general circulation model (Bryan et al., 1988). The normalized response is multiplied by 100, and the atmospheric carbon dioxide is doubled. Note the delayed response high latitudes of the Southern Hemisphere.

equilibrium. In light of the fact that the climate system has many complex feedback mechanisms, the basic problem in interpreting the energy balance model results is that the model must be calibrated with the present climate. We cannot be sure of the results when the model is applied to a very different regime. In particular, the energy balance model oceans are calibrated using transient tracer data to provide a measure of vertical mixing. This procedure can be justified only for very small perturbations of temperature, since temperature anomalies affect the buoyancy field of the ocean while neutrally buoyant tracers do not. Feedback effects on the buoyancy field which may become important early in the next century can only be explored in the more detailed models of the ocean to be discussed in the next section.

4. Coupled Ocean and Atmospheric General Circulation Models

Recently the distinction between medium-range numerical weather prediction models and research climate models has become increasingly blurred. Since the various parameterizations of physical processes are finding their way into operational forecasting models, the main difference between operational medium-range models and climate research models is now in the horizontal resolution. As a result the atmospheric general circulation models are receiving a great deal of attention and have been extensively validated as forecast models. For obvious reasons equal attention has not been paid to the development and validation of ocean models, and climate research with coupled models of the atmosphere and the ocean is still in its infancy.

The basic dynamics of the ocean and the atmosphere are the same. One would think that ocean modelling would require only a straightforward adaptation of techniques used in atmospheric modelling. However, there are special features of the ocean that make this very difficult. One feature is the very great range of energy-containing spatial scales in the ocean relative to the atmosphere. Important currents are quite narrow, requiring detailed horizontal resolution for an accurate simulation. Another feature is the very long time scales of the ocean resulting from both the very slow propagation of important large-scale waves, and the ocean's enormous heat capacity. Thus the ocean is very wide banded with respect to frequency and spatial wave number relative to the atmosphere.

The oceanic equivalent of cyclones and anticylcones in the atmosphere are oceanic mesoscale eddies which are over an order of magnitude smaller than their atmospheric counterparts in middle latitudes, and are even smaller in polar regions. For example, a mesoscale eddy in the Gulf Stream has a scale of only a few hundred kilometers in comparison with a horizontal scale of thousands of kilometers for atmospheric disturbances. An important controversy among oceanographers concerns the role of mesoscale eddies. Can a model of the ocean be devised without explicitly resolving mesoscale eddies which will be adequate to represent the downward pathways for heat and tracers? Some insight on this question is available from a study by Cox (1985) in which the tracer penetration in eddy-resolving and non-eddy resolving models was carefully compared. It was found that the mixing by mesoscale eddies can be quite effectively parameterized, as suggested by Redi (1982), by rotating the mixing tensor so that it is aligned with density surfaces rather than with horizontal surfaces. Another approach to answering this question is strictly empirical, through comparison of model simulations with transient tracer data and water mass properties. An example is the comparison of GEOSECS tritium data with the simulation of the non-eddy resolving Hamburg model shown in Fig. 1. Given the uncertainties of the transient tracer input data, it is not clear whether an eddy-resolving model would provide a result which would be better in a statistically-significant sense.

The non-equilibrium problem of climate change can be studied only with fully coupled models. Since fully coupled atmosphere-ocean general circulation models are still under development, relatively little work has been done on this challenging problem. Response to greenhouse warming involves the exchange of heat between the surface and deeper water at both high and low latitudes, and thus requires a much more general model of the oceans than that required for modelling the El Niño-Southern Oscillation phenomenon. Two published studies of coupled ocean-atmosphere general circulation models by Bryan et al. (1982) and Schlesinger et al. (1985) have examined the effects of a sudden increase of atmospheric carbon dioxide. We will refer to these model studies as "switch on" numerical experiments. The first experiment (Bryan et al., 1982) was carried out for a very idealized geometry consisting of a 120° longitude sector bounded by two meridians running from the equator to the pole. Half of this area was covered by land and the other half by ocean. Mirror symmetry was assumed across the equator, and cyclic symmetry assummed at the meridional boundaries. Clouds were fixed and seasonal effects were not included in the model. Two equilibrium climates were determined, one corresponding to a normal level of CO_2 in the atmosphere, and one corresponding to four times the normal level. It would be impractical to find the climate equilibria by extended numerical integrations, because of the very long time scales of the deep ocean. To circumvent this problem special methods (Bryan, 1984) were utilized to accelerate convergence. The results in Fig. 2(b) show the zonally averaged surface air temperature as a function of the number of years after "switch on." The results can be compared directly with the global energy balance model results of North et al. (1984) shown in Fig. 2(a). It is reasonable to compare Fig. (2)b with the Northern Hemisphere results in Fig. 2(a) since the proportion of ocean to land is much greater than 1:1 in the Southern Hemisphere. It is evident that the ocean general circulation model takes up much more heat than the passive ocean in the North et al. (1984) model. After 25 years the normalized response is about 0.7 in the coupled general circulation model, while the same normalized response is reached in about 5 years in the coupled energy balance model. However, as pointed out earlier, the response time is very much a function of the feedbacks in the model. If cloud feedback had been included in these models, one might expect a much slower approach to the new equilibrium.

The first "switch on" calculation for a coupled general circulation model with true global geometry was carried out by Schlesinger et al. (1985). The ocean component has very much the same structure as that used by Bryan et al. (1982), while the atmospheric model was a finite difference two-layer model which has been extensively validated. Seasons and variable cloudiness were included in the atmospheric model. Rather than attempting to find a climate equilibrium for the coupled model, the "switch on" experiment was performed and the climate drift subtracted from the response. The sea surface temperature was predicted by the model, but the sea surface salinity was kept fixed as specified by observations. The results showed a nearly symmetric response in both hemispheres.

Recently, another "switch on" calculation (Bryan et al., 1988) has been completed which suggests that the "greenhouse" warming may not be symmetric in both hemispheres. The geometry of the ocean-to-land distribution is idealized, but care is taken to have the exact ratio of land to ocean at each latitude correspond to the Northern and Southern Hemisphere. Equilibria are obtained for climates corresponding to one and two times the carbon dioxide now in the atmosphere. Then the normal climate is perturbed by doubling the atmospheric CO_2 and the non-equilibrium response is monitored over a 50-year period. Both temperature and salinity in the oceans are free to adjust at the surface and deeper levels to the new fluxes of heat and water dictated by the atmospheric model. The normalized surface air response is shown in Fig. 2c. The predominantly land hemisphere, corresponding to the Northern Hemisphere, warms at about the same normalized rate predicted in the earlier calculation by Bryan et al. (1982) corresponding to a quadrupling of atmospheric carbon dioxide. On the other hand, the Southern Hemisphere warms at a much slower rate. Much slower, in fact, than predicted by the energy balance model results shown in Fig. 2(a). Analysis of the results show that there are two factors involved in the slow response of the predominantly ocean-covered hemisphere. One, the large extent of ocean allows greater heat storage. This effect was predicted by Thompson and Schneider (1982). Two, the very deep overturning of the ocean in the vicinity of the Antarctic Circumpolar Current, which is simulated in this model, sequesters heat very efficiently at deep levels in the ocean in the predominantly ocean-covered hemisphere. Thus the polar amplification of the greenhouse warming predicted by an equilibrium response calculation may not be seen in the Southern Hemisphere in a period of very rapid greenhouse warming.

5. Summary

The basic driving force for global greenhouse warming is the changing abundance of radiatively active gases in the atmosphere. The actual response in the near term of climate to a greenhouse warming event will depend on the large-scale interaction of the ocean and atmosphere. Attempts have been made to project climate change by assuming that the ocean responds passively to greenhouse warming as predicted by linear models calibrated from transient geochemical tracers. Coupled atmosphere-ocean experiments at this point are preliminary and do not provide consistent results. However, it is clear that the simpler models of the ocean's response are probably inadequate in the case of a rapid increase of greenhouse gases. A great deal of effort will be required to make reliable climate projections. The most obvious research directions are:

(a) Continued study of transient tracers in the ocean. The ocean component of coupled models must be validated using the transient tracer data.

(b) Historical climate records and paleoclimatic records must be carefully examined for information on the role of the oceans in modifying climate change.

(c) The equivalent of the effort that has gone into perfecting general circulation models of the atmosphere must now be devoted to developing models of the ocean and land surfaces.

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